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The Search for energy source of Crab Nebula

Gamma-ray group report

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Outline

- Introduction

  Crab Nebula, Radius vs Mass diagram, Telescopes

- Measure pulsar with Fermi Satelite

  Pulsar, Pulsar’s period

- LST analysis

  Measurement of its direction, flux

- analysis results

  Rotation speed, Centrifugal Force, Luminosity, Eddington Limit

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Introduction

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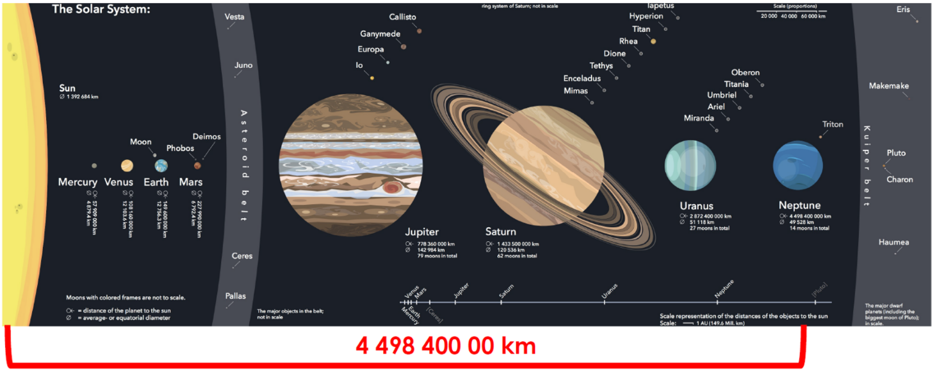
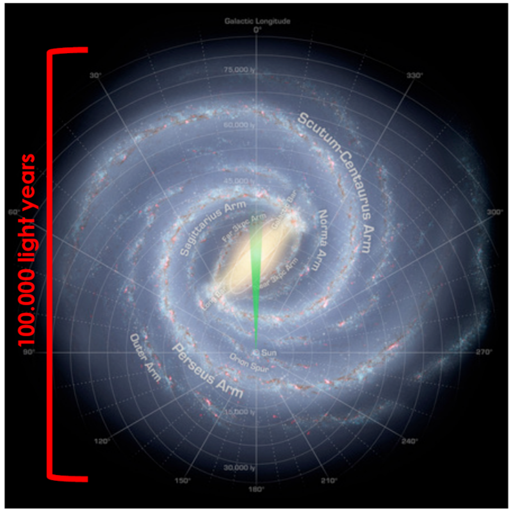
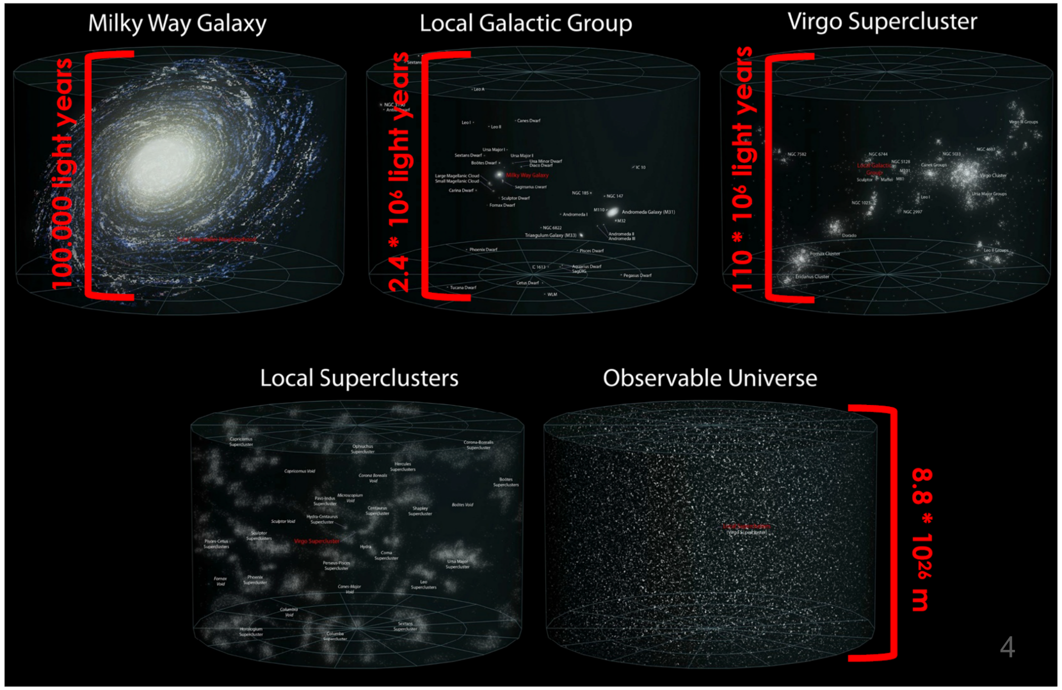
Our universe





Our planet Earth is very large, but the universe surrounding it is far more than that

Countless celestial objects in it emit energy, which reaches our earth in various forms



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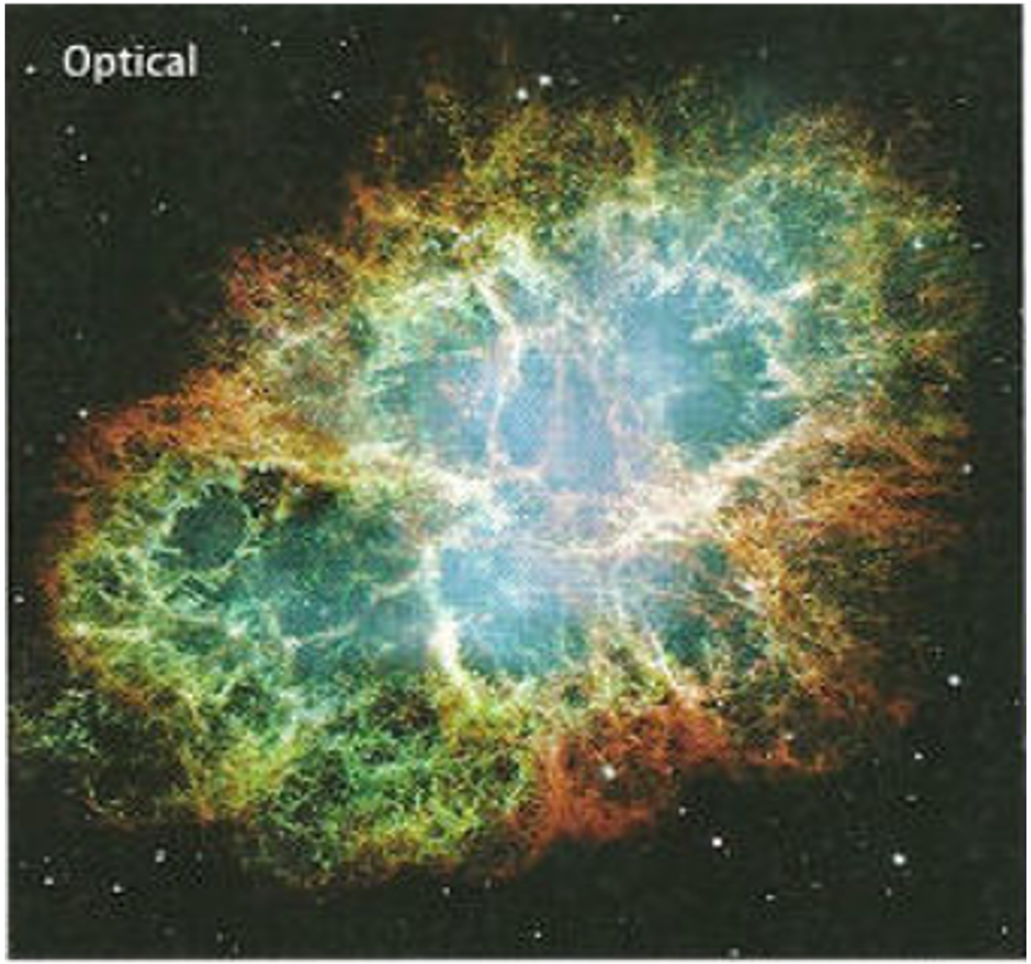
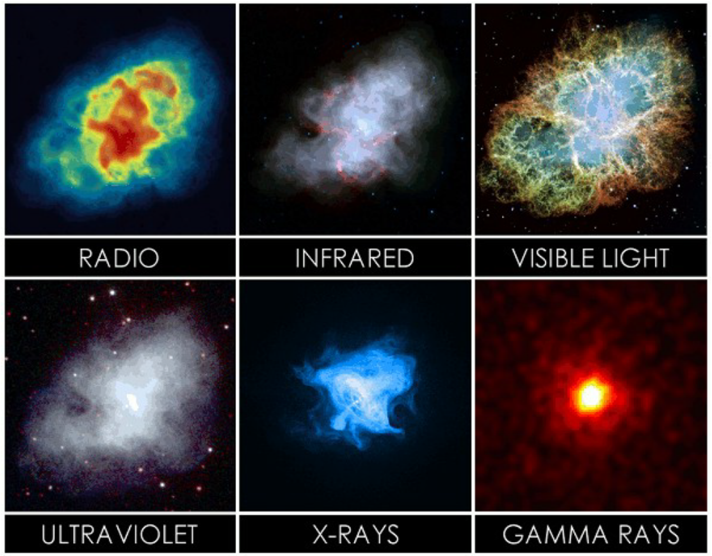
Crab Nebula



Crab Nebula is very bright gamma source

Typical pulsar wind nebula and it is used for calibration of instrument about gamma-ray astronomy



What is Crab Nebula?

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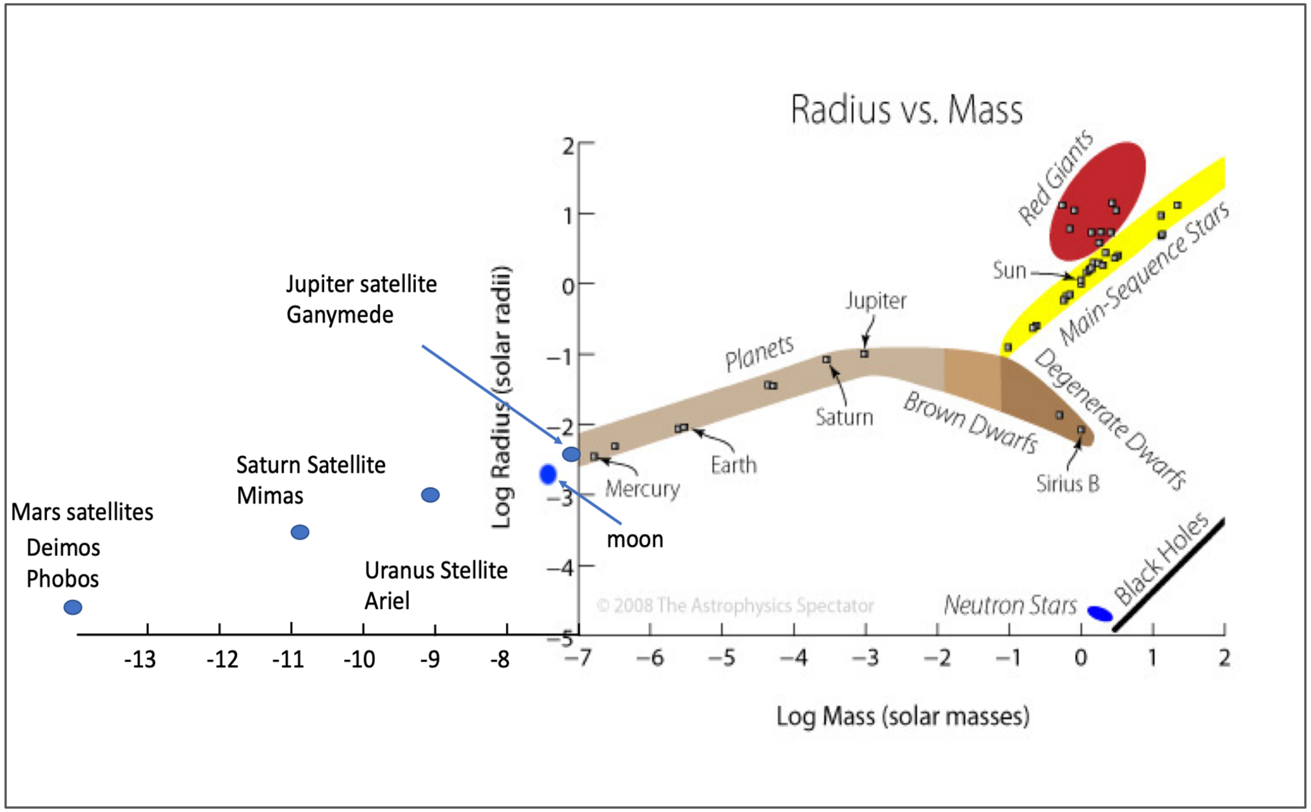
Radius vs Mass diagram

This figure shows the radius and mass distribution of the known objects

Planets and stars are distributed along a line, with red giant stars, neutron stars, and black holes slightly out of the sequence

We would like to use this figure to clarify what the energy source of the Crab Nebula is !



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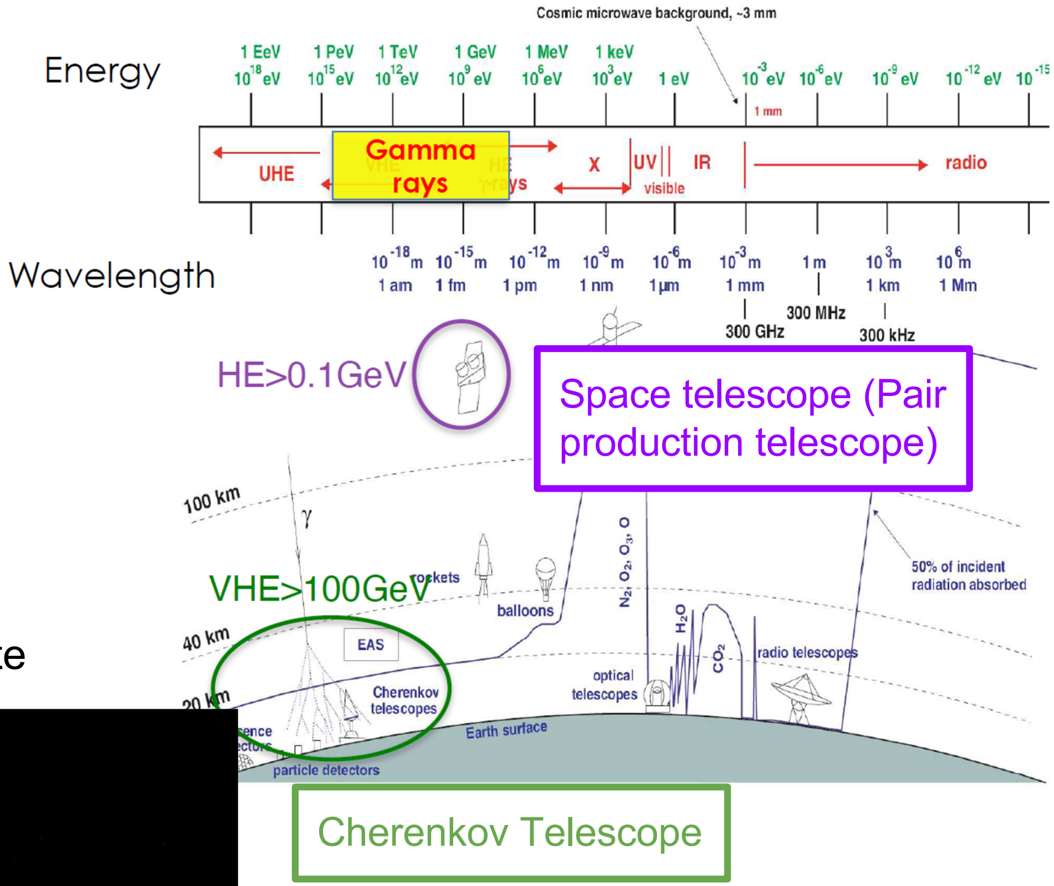
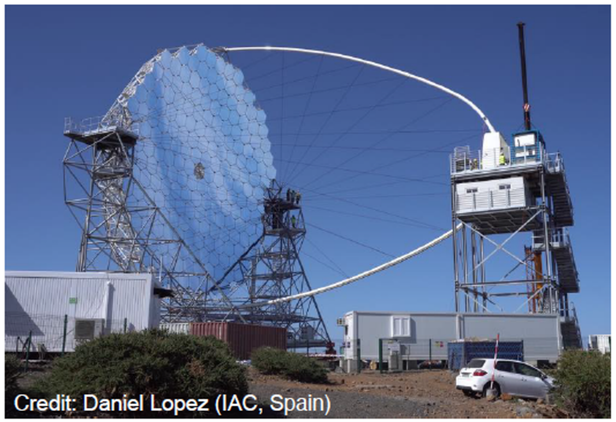
gamma ray

The energy range of gamma-ray is from 0.1MeV.

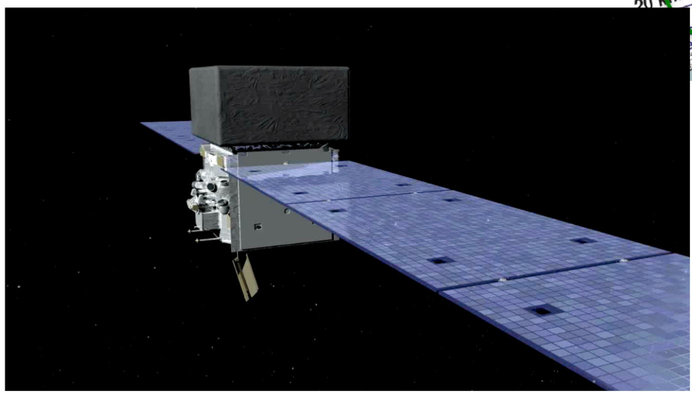
We use data of gamma ray from pair production telescopes and Cherenkov telescopes



CTA LST-1



Fermi Satelite



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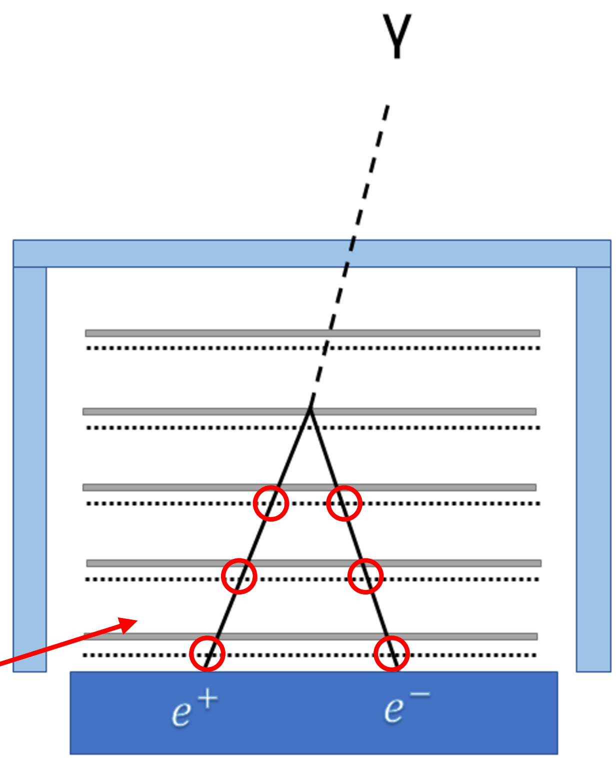
Gamma-ray Space Telescopes

Gamma rays absorbed by the atmosphere when they reach the earth.
Direct observation requires sending a satelite into space.

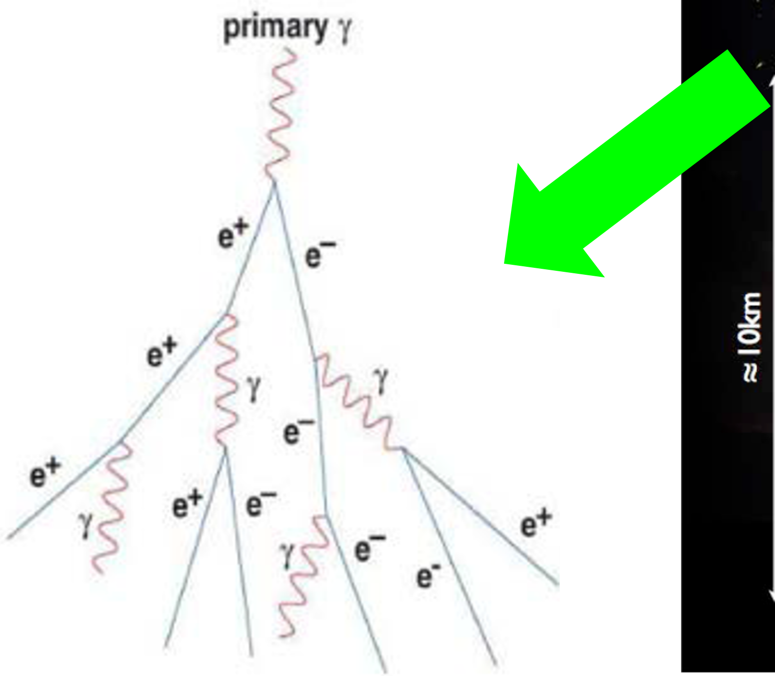
Gamma ray converts to an e^+, e^- pair in a high density foil layer

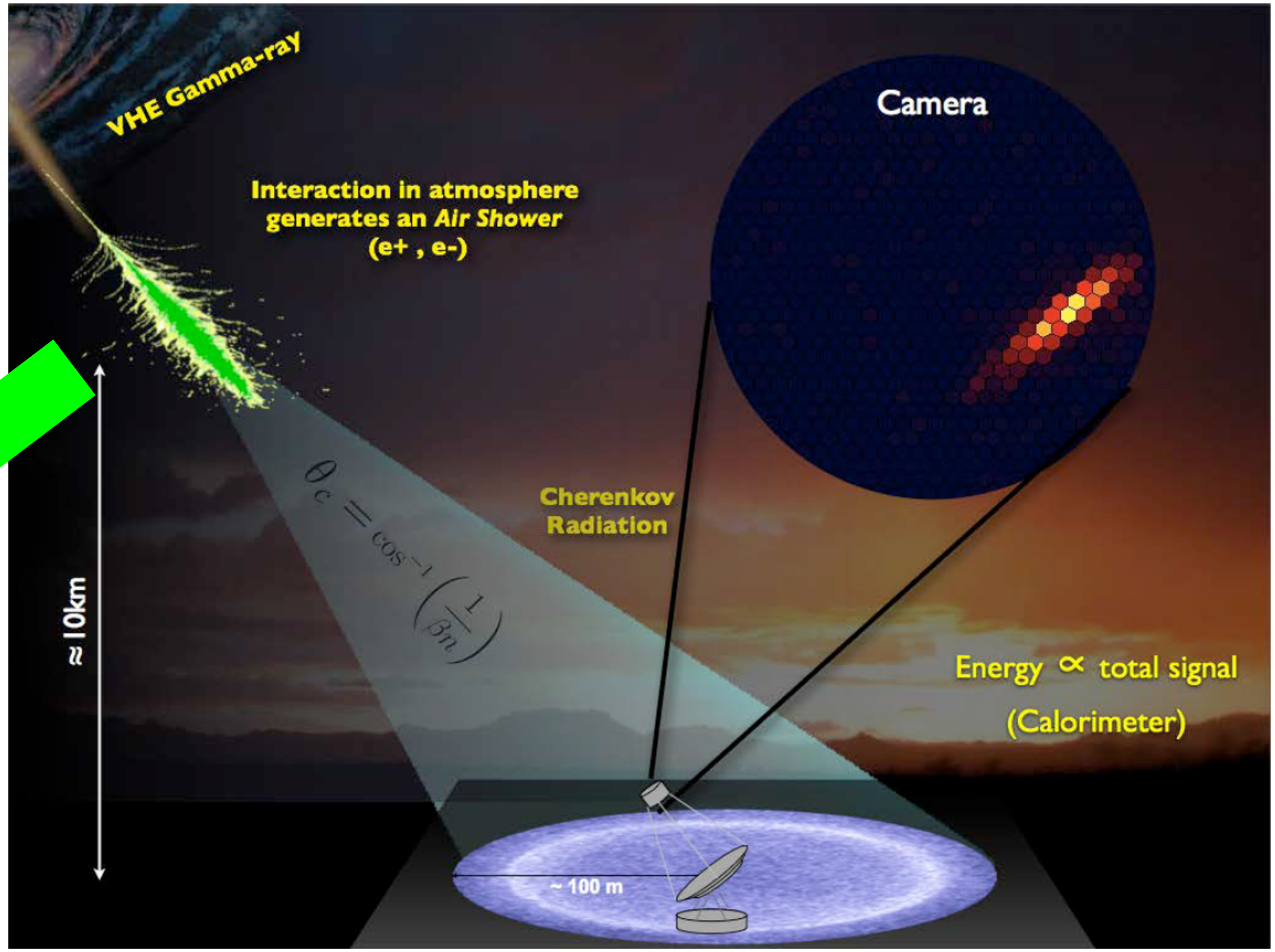


The track of charged particles in the instrument reveals the presence of gamma rays and their direction of arrivals

Cherenkov Telescopes

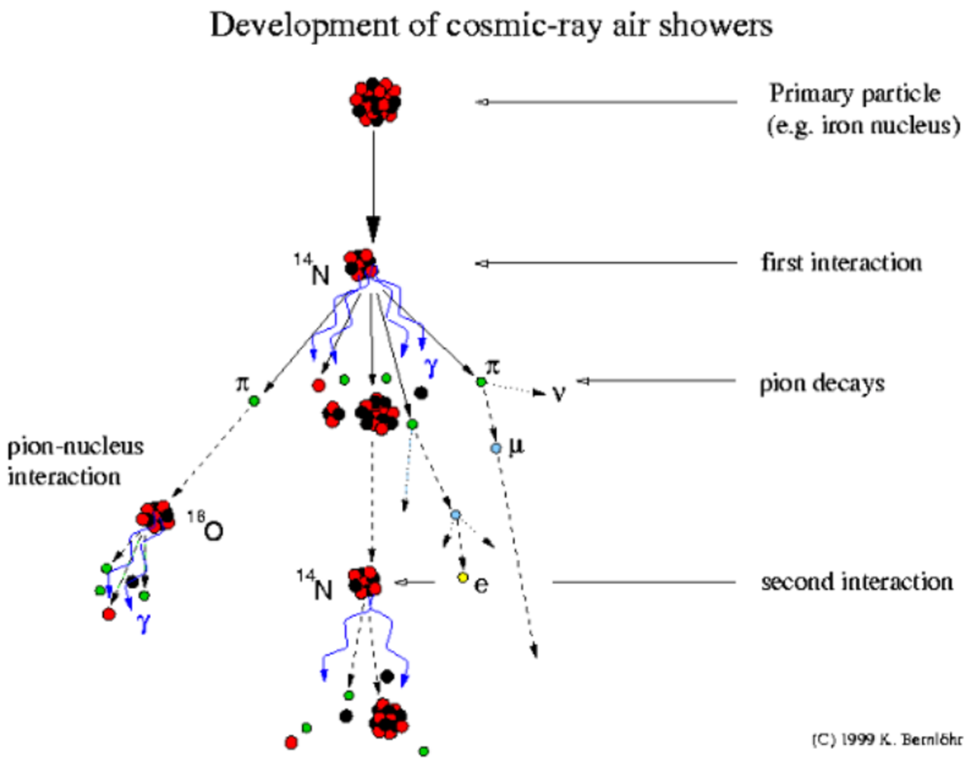
High-energy gamma rays produce air showers when they enter the atmosphere





Hadronic shower

Hadron



Cosmic rays also interact with the atmosphere, producing showers

- Nuclear interaction
- pion decay

Need to get rid of this background !

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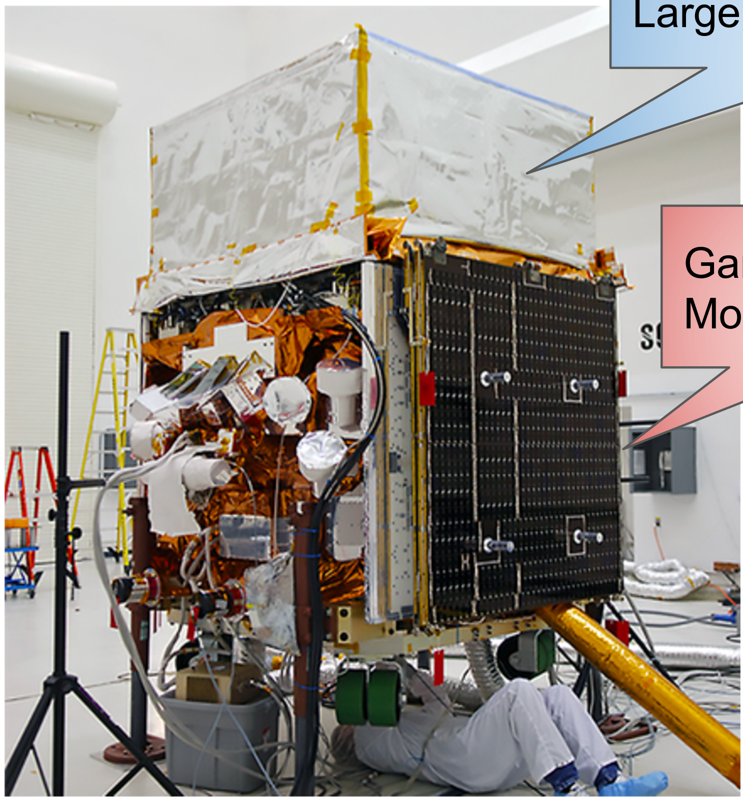
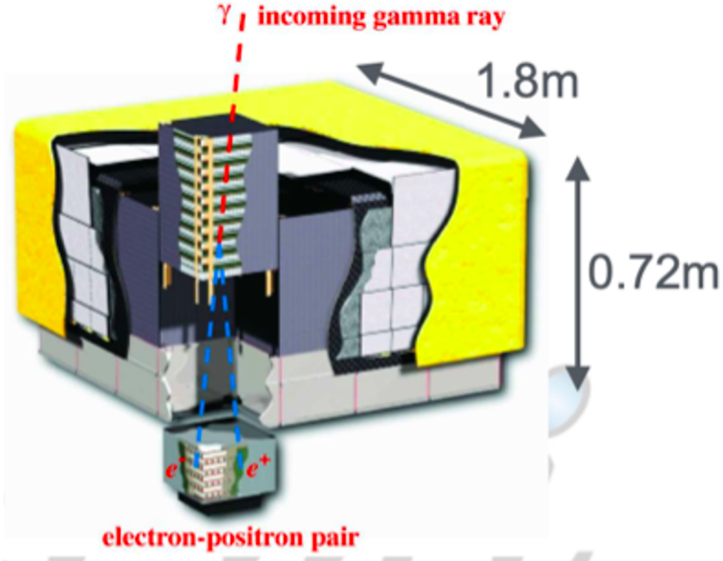
Fermi Satellite analysis of Crab pulsar

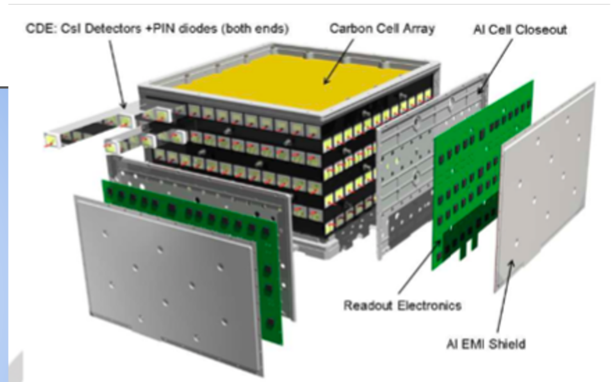
Fermi Satelite



Large area Telescope(LAT)

Gamma-ray Burst Monitor(GBA)





Composed of
- Tracker (TKR)
- Calorimeter(CAL)

Surrounded by
- Anti-coincidence detector (ACD)

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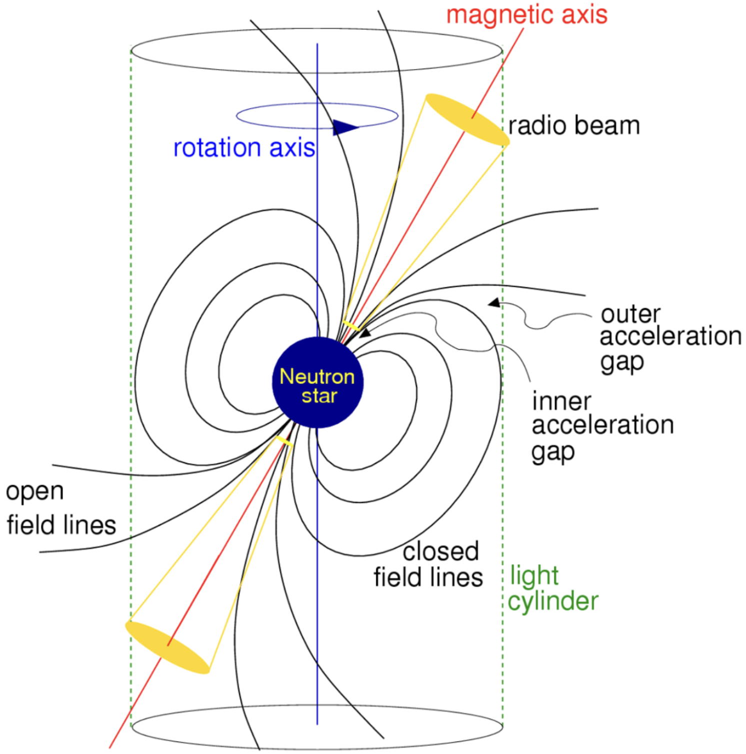
What is Pulsar



Pulsars... strongly magnetized spinning neutron stars

- very massive, but very compact
- can be described as rotating dipoles
- known to radiate from radio to high-energy
- <u>quickly spinning</u>

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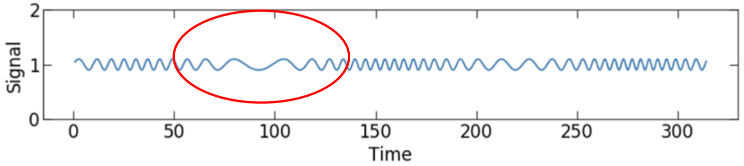
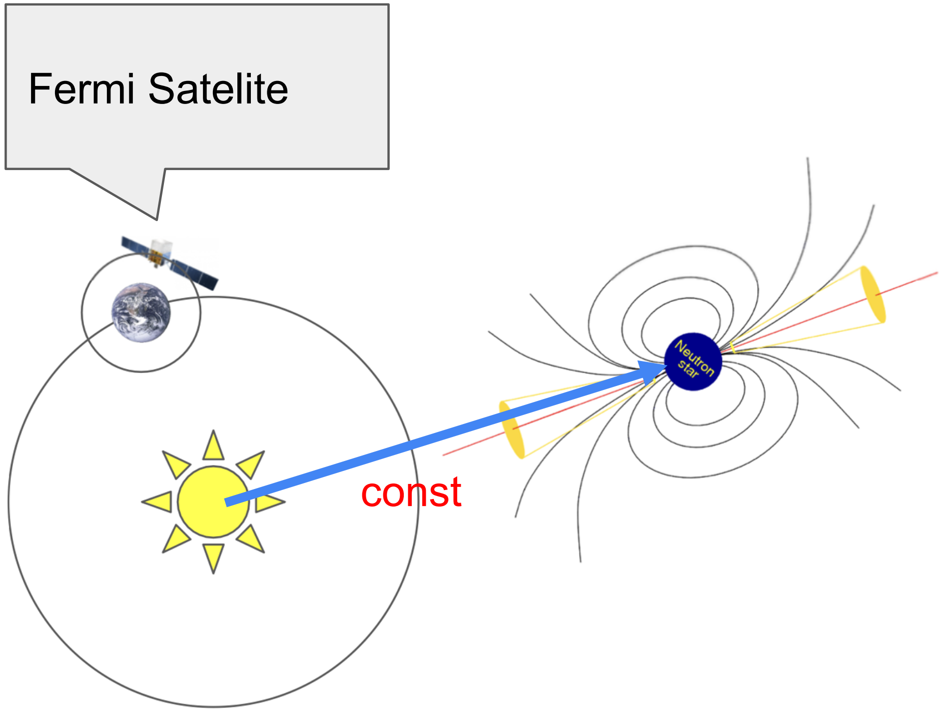
Measuring Real time pulsars



The observed signal is not periodic

- spacecraft orbital movement
- Earth orbital movement
- gravitational time delay due to Sun



So, we need **So-called “barycentric” correction**

(Brings all the measurement time to the Solar System center)

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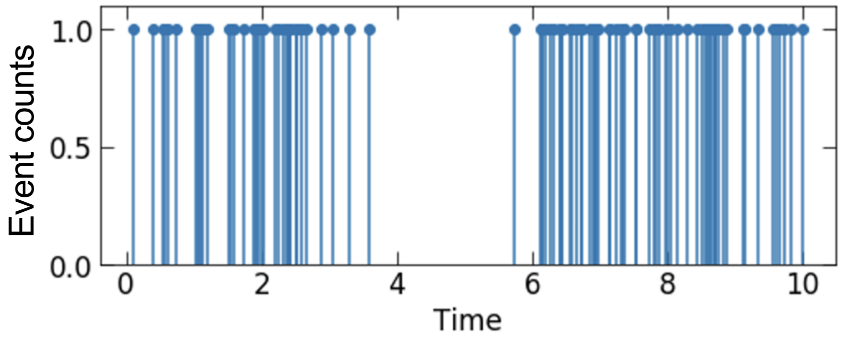
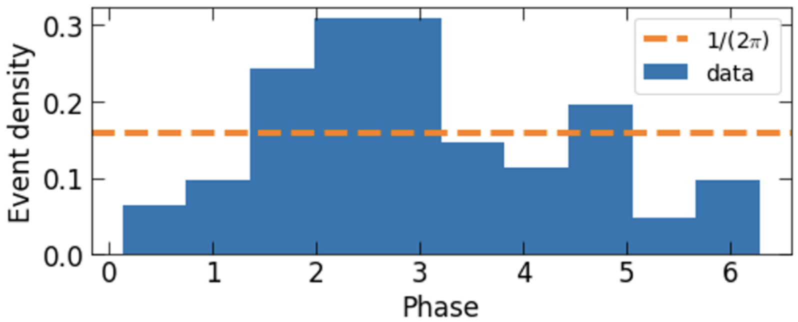
Find periods





- Let’s consider signal in "phase" by assuming <u>ω=const</u>
  - $\theta=\omega t$: phase for each event

$$p_i = (f^0 t + f^1 \frac{t_i^2}{2} + f^2 \frac{t_i^3}{6})$$

- $f(\theta)$: signal vs phase
  - if $f(\theta)$ is wrong periods
    - data will be <u>flat</u>
  - if $f(\theta)$ is correct periods
    - <u>wave</u> can be seen

- So, we need to <u>find NOT the flattest phase</u>

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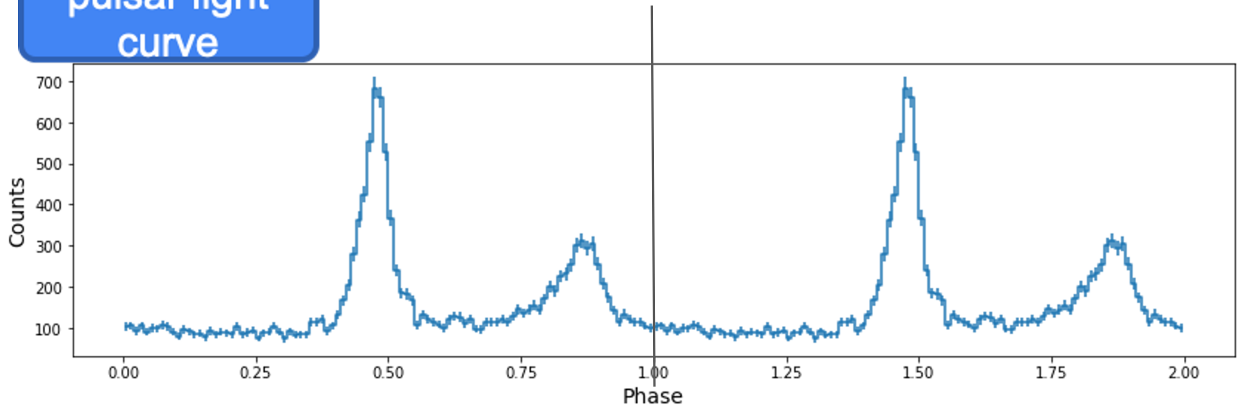
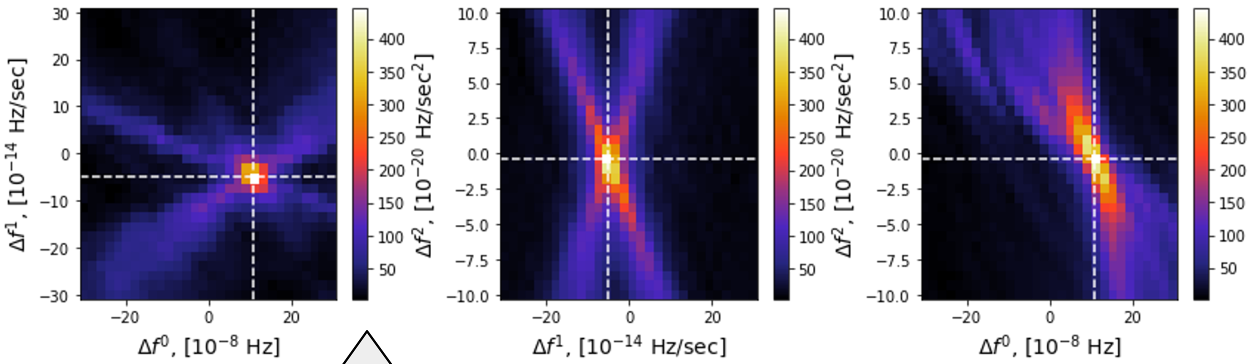
The results

pulsar light curve





f_0, f_1 shift

f_1, f_2 shift

f_0, f_2 shift

Poissonian likelihood value (logarithm)

- we found the best phase distribution
- The bright colors in the figure show the most probable values.

↓

- We got frequency

$$f_0 = 29.623833 \text{ Hz}$$
$$f_1 = \text{-}3.685842\text{e-}10 \text{ Hz/sec}$$
$$f_2 = 1.333333\text{e-}20 \text{ Hz/sec\^{}2}$$

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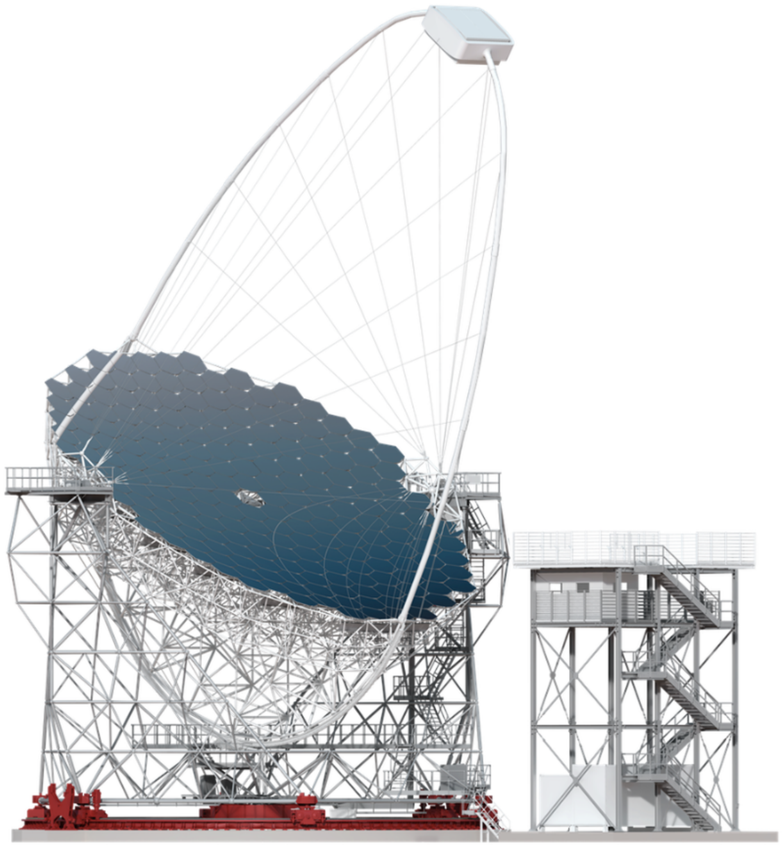
LST analysis

LST (Large-sized Telescope)



Credit: G. Pérez, IAC, SMM

- 23m diameter Cherenkov telescope
- There will be 4 LSTs in La Palma (Spain) in the northern hemisphere and possibly also in the southern hemisphere
- Could measure **GeV to TeV** scale (very-high energy) gamma rays
- **1st LST** has already been constructed and started measurement from 2018

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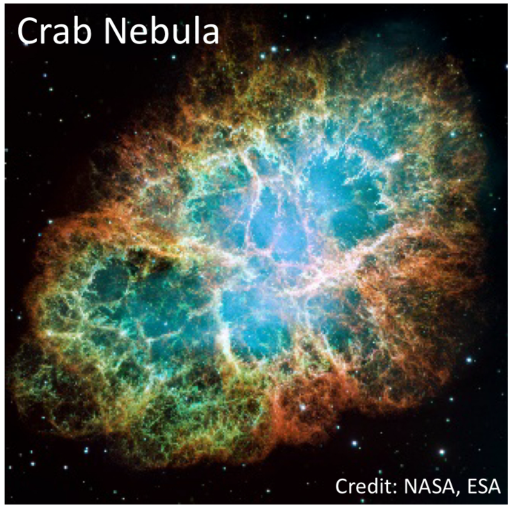
Measurement by LST

Measurement of **gamma rays** from objects like Crab Nebula

Gamma radiation gives us the important information such as time fluctuation, energy and location etc.

We can characterize objects in other energy ranges like X ray and radio.



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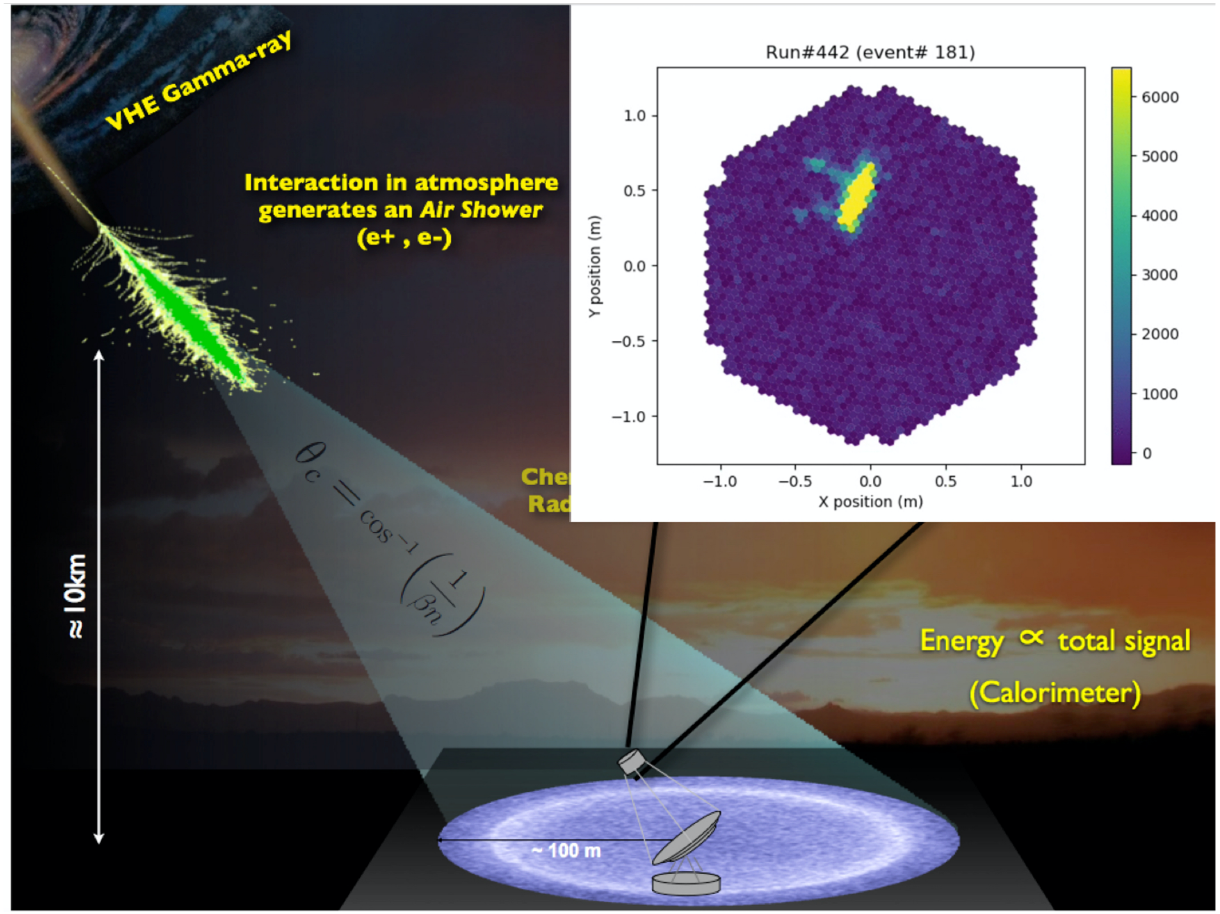
LST camera image and our data



We count one Cherenkov image as one event

The Cherenkov light is detected with PMTs (photomultiplier tube) and is shown as image

Each event only lasts a few nano seconds

<Our data>

we measured 19.2 mins

All events 5,023,412

But it includes many many other cosmic rays (background)

So we need to exclude background events firstly! This is very important!

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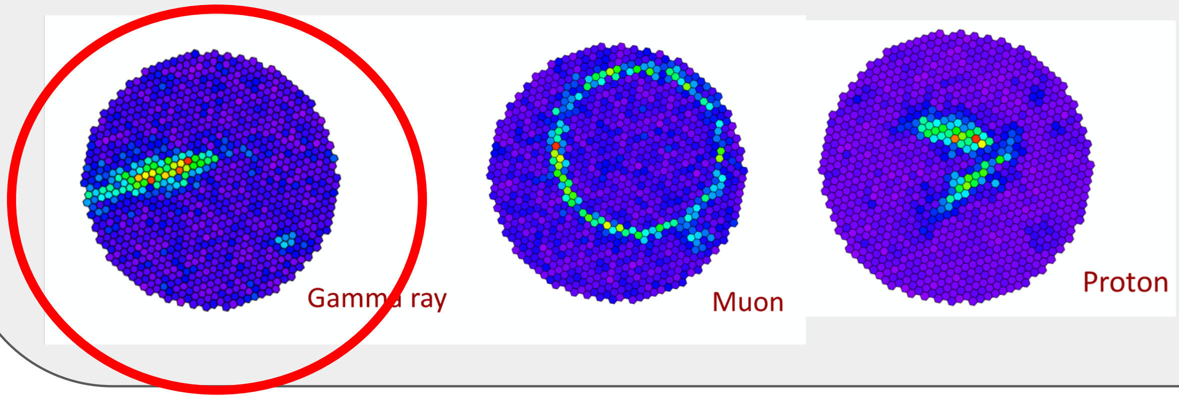
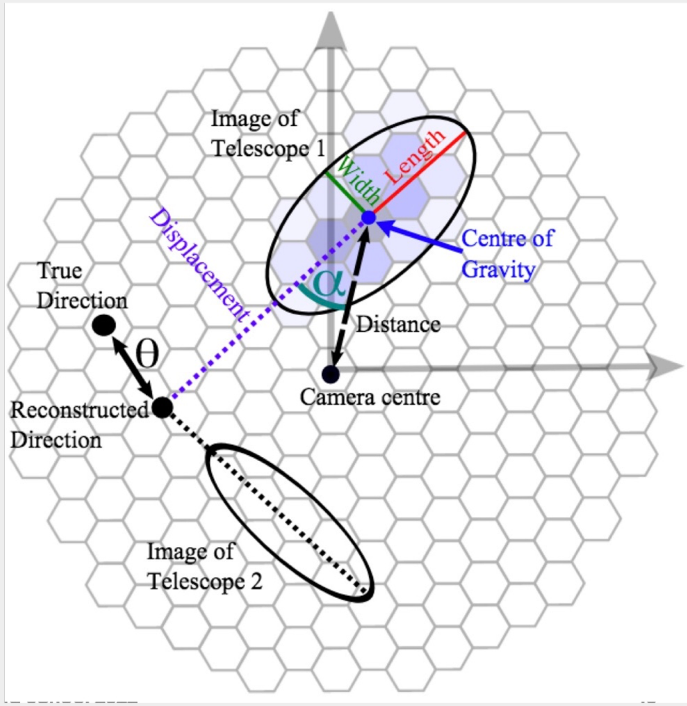
How to exclude background events

1st step. Machine learning

Images look different for different particles like below
Machine learning evaluate likeliness of gamma-ray,
called "gammaness"





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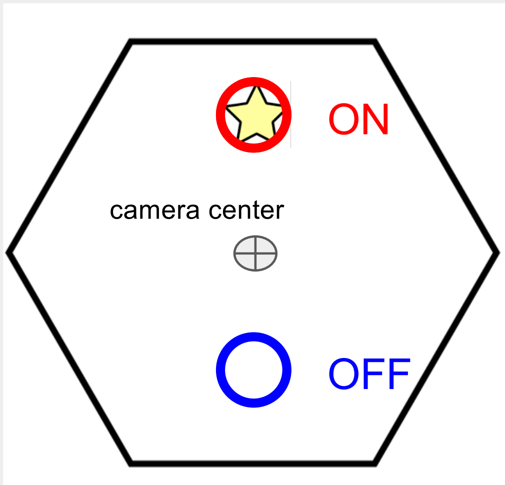
How to exclude background events

2nd step. On/Off cutting

ON region : Gamma and background
OFF region : Only background

We can subtract the OFF number as background from ON number!



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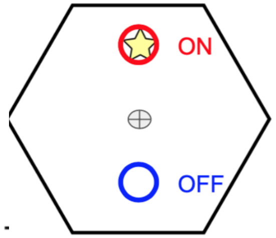
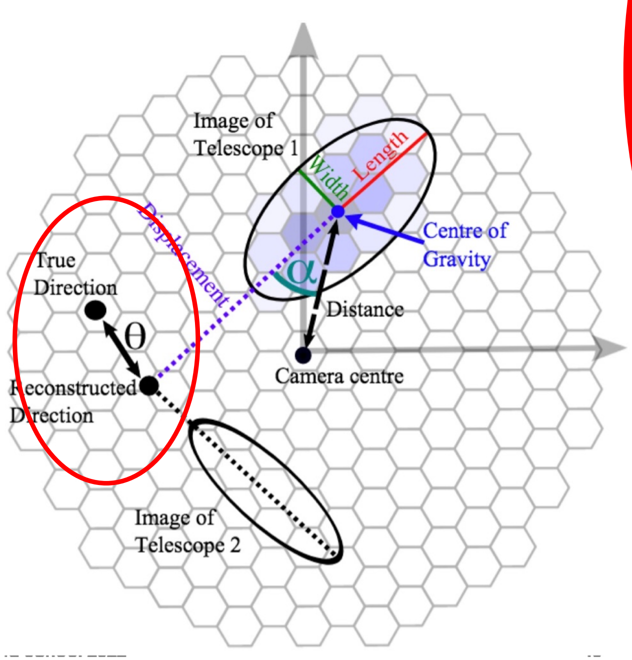
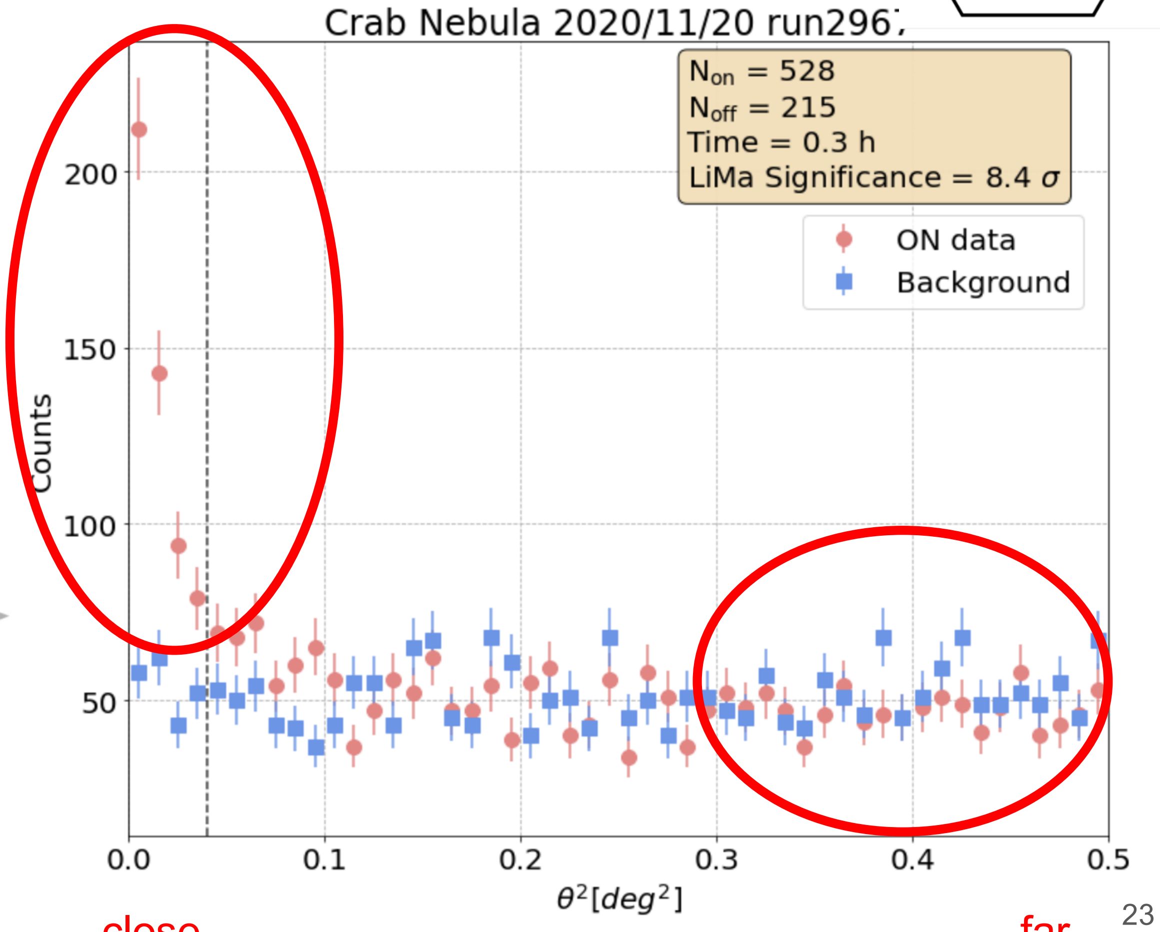
LST measurement result1 - θ^2 plot-



θ shows distance between object place already know and estimated place on celestial sphere

$\theta^2=\theta_x^2+\theta_y^2$





Distribution of gamma ray and cosmic rays

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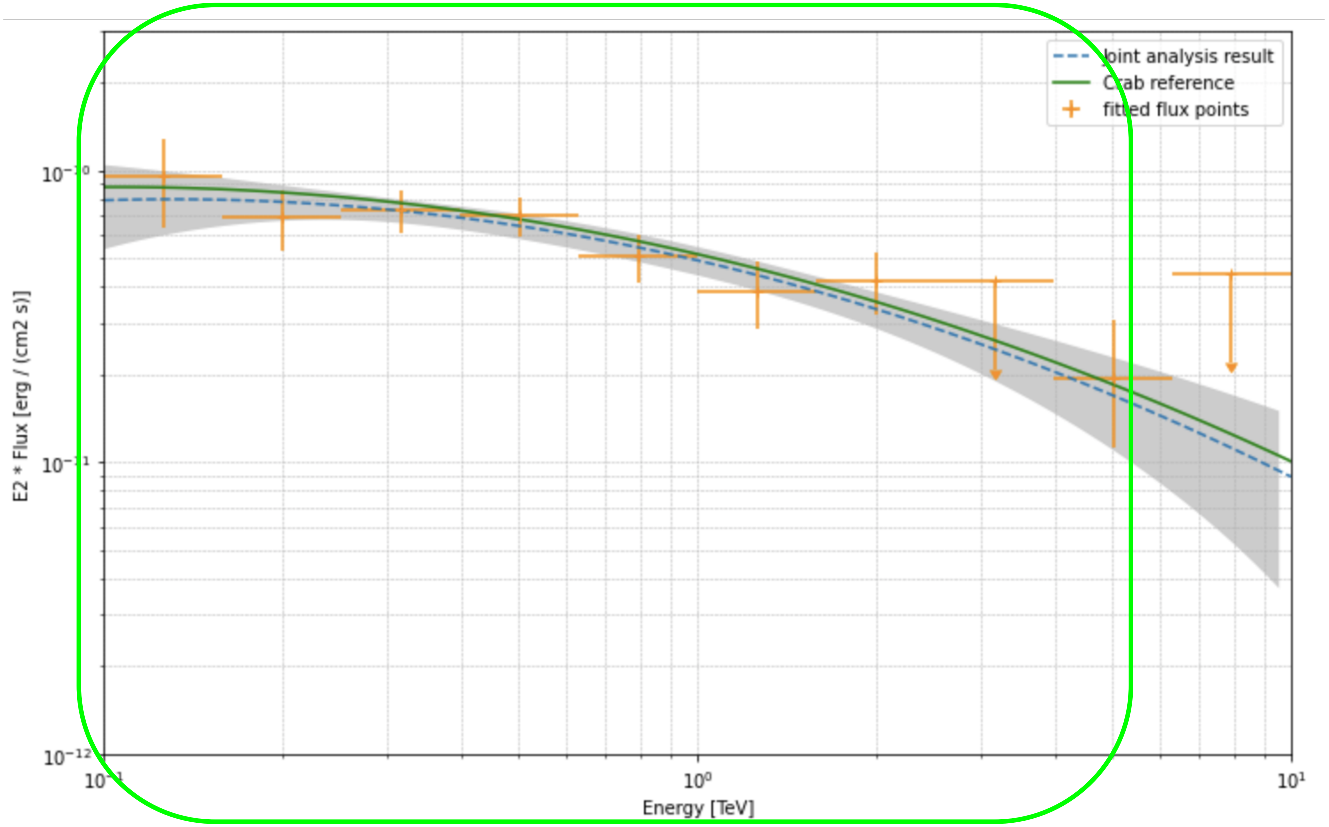
LST measurement result2 - Flux-



100(Gev)

5(Tev)

We obtained flux of gamma-ray from 100 GeV to 5 Tev

We integrate,

Flux = 2.14 x 10^{-10} erg /cm^2 s

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Analysis Result

From the arguments below, Mass-Radius Diagram limitation is obtained.

1. Rotation Speed at Equator vs Light Speed
2. Centrifugal Force vs Gravitation
3. Spindown Luminosity vs Power of Rotation
4. Eddington Limit

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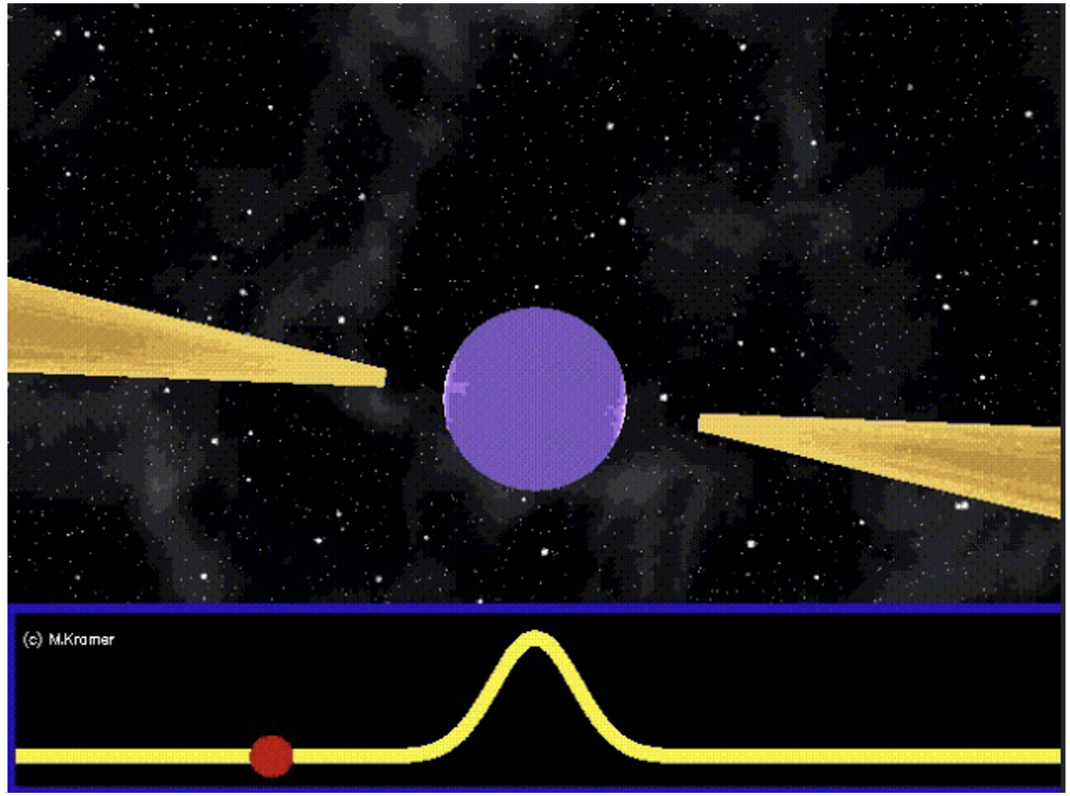
Rotation Speed at Equator vs Light Speed



1. Considering Pulse period equals celestial body rotation period.

1. speed at equator < speed of light

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Rotation Speed at Equator vs Light Speed

From Fermi analysis, pulse period f_0 = 29.62 Hz.

Therefore, radius upper limit should be like below:

$$R < \frac{c}{\Omega} = \frac{c}{2\pi f_0} \simeq 1.6 \times 10^3 \, \mathrm{km}$$

$$\therefore \; r := \frac{R}{R_{\mathrm{sun}}} < 2.3 \times 10^{-3}$$

$$\log r < -2.6 \qquad (1)$$

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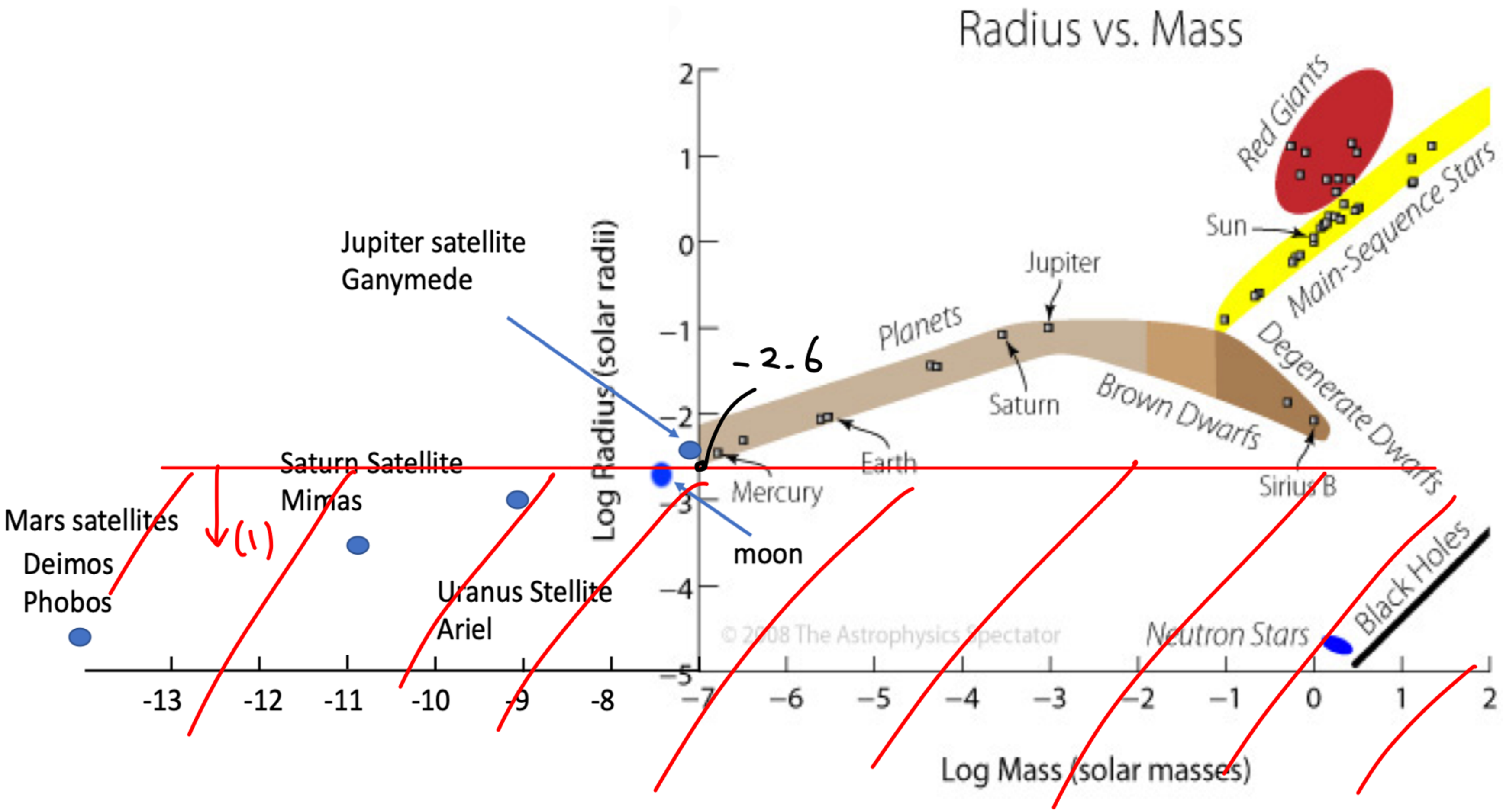
Mass Radius Limitation (1)



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Centrifugal Force vs Gravitation

At the surface of the celestial body, the following should hold:

$$\underbrace{mR\Omega^2}_{\text{centrifugal force}} \quad < \quad \underbrace{G\frac{Mm}{R^2}}_{\text{gravitation}} \quad .$$

From above, we get the 2nd inequality:

$$R < \sqrt[3]{\frac{GM}{\Omega^2}} = \left\{ \frac{GM_{\text{sun}}}{(2\pi f_0)^2} \frac{M}{M_{\text{sun}}} \right\}^{\frac{1}{3}}$$

$$\therefore \ r < 2.2 \times 10^{-4} m^{1/3} \quad \left(m := \frac{M}{M_{\text{sun}}} \right)$$

$$\log r < \frac{1}{3} \log m - 3.7 \qquad (2)$$

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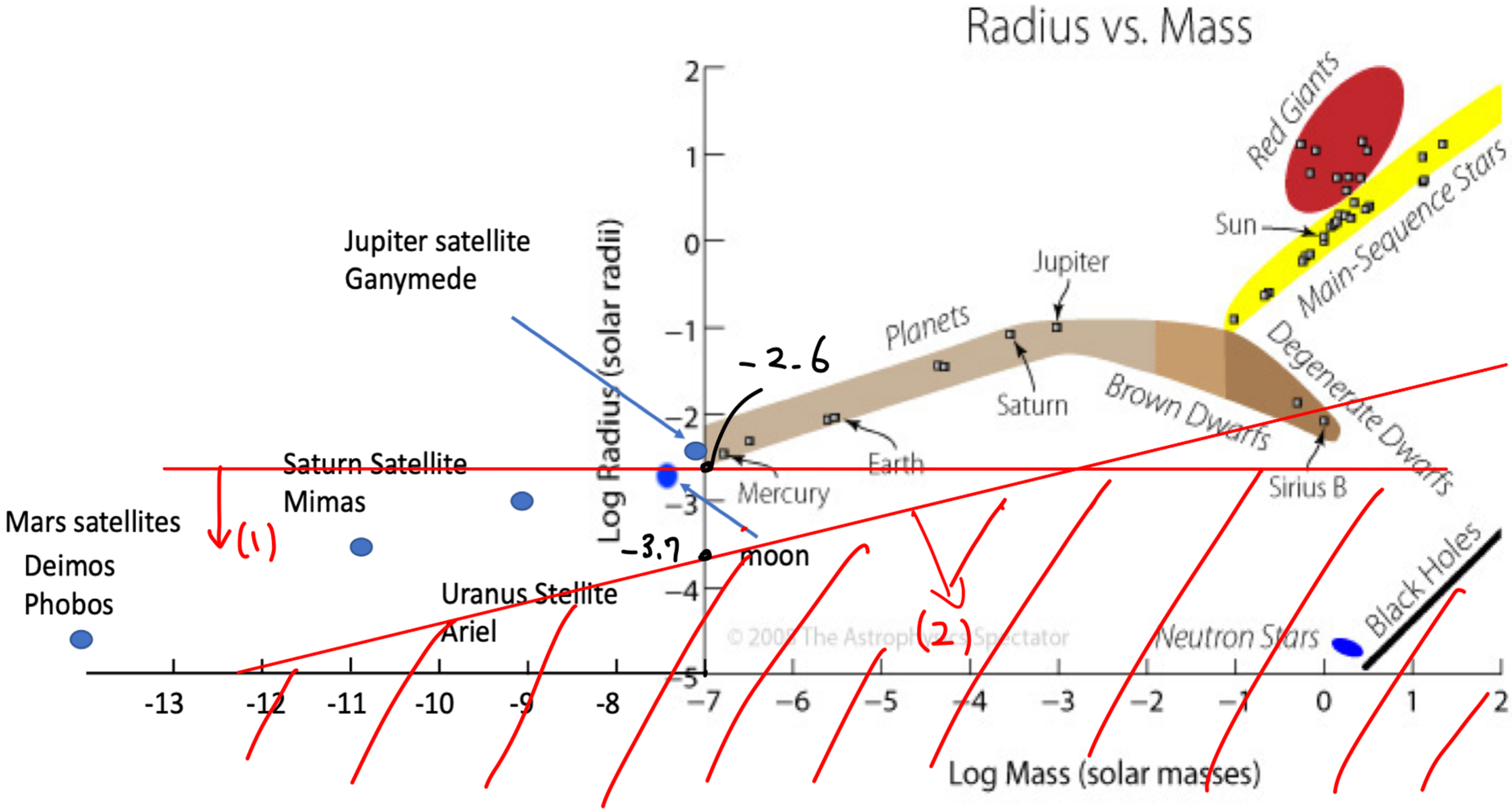
Mass Radius Limitation (2)



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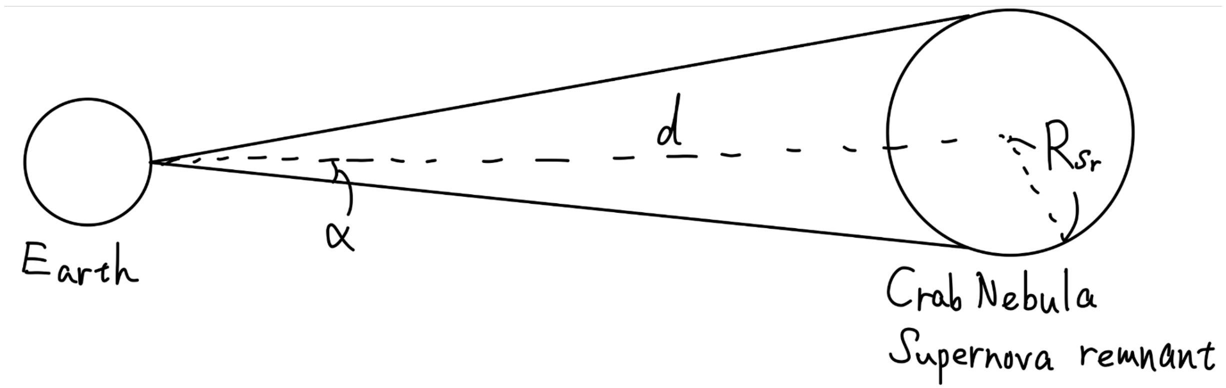
Distance from the Earth to Crab Nebula

1. Crab Nebula Supernova is known to have occurred 1054 A.D.(:= t_0).
2. Assume average speed of Supernova remnant V = 1500 km/s, supernova remnant size is estimated to be

$$R_{\mathrm{Sr}} = V(t_{\mathrm{today}} - t_0) \simeq 1.5\,\mathrm{pc}.$$

1. α is 2.7 arcmin (observation data)



Thus,

$$d = \frac{R_{\mathrm{Sr}}}{\tan\alpha} \simeq \frac{R}{\alpha}$$
$$= 1.9\,\mathrm{kpc}.$$

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Luminosity of Crab Nebula

Flux f is obtained from LST analysis. Therefore, luminosity of Crab Nebula is

$$
\begin{aligned}
L &= 4\pi d^2 f \\
&= 4\pi \times (1.9\,\mathrm{kpc})^2 \times 2.14 \times 10^{-10}\,\mathrm{erg\,cm^{-2}\,s^{-2}} \\
&\simeq 9.25 \times 10^{34}\,\mathrm{erg\,s^{-1}}.
\end{aligned}
$$

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Spindown Luminosity vs Power of Rotation

Luminosity is a radiant electromagnetic power emitted by a celestial body.

Suppose luminosity is caused by a spindown of Crab Nebula, following relation should hold:

$$\underbrace{L}_{\text{luminosity}} < \underbrace{\left|\dot{E}\right|}_{\text{power of spin rotation}}$$

$$\left(E = \frac{1}{2} I \Omega^2, \ I = \frac{2}{5} M R^2\right)$$

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Spindown Luminosity vs Power of Rotation

From Fermi analysis, f_0 = 29.62 Hz, f_1 = -3.66 × 10^{-10} Hz/s. Then the luminosity–power relation is transformed like below, and the 3rd inequality is gained:

$$
\begin{aligned}
MR^2 &> -\frac{5}{8\pi^2}\frac{L}{f_0 f_1} \\
&= 5.40 \times 10^{34}\,\mathrm{kg\,m^2} \\
mr^2 &> 5.60 \times 10^{-14} \\
\log r &> -\frac{1}{2}\log m - 6.6 \quad (3)
\end{aligned}
$$

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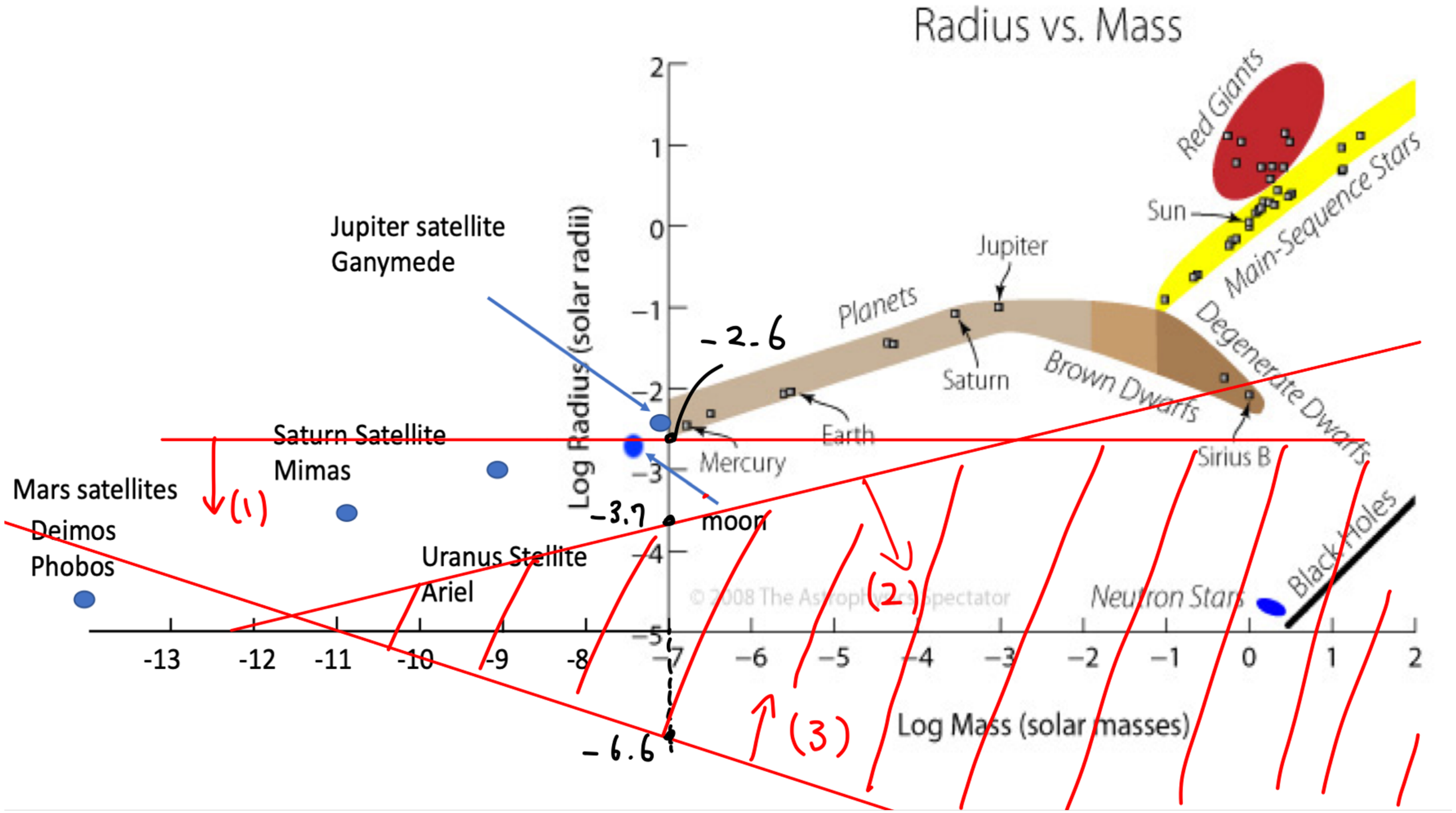
Mass Radius Limitation (3)



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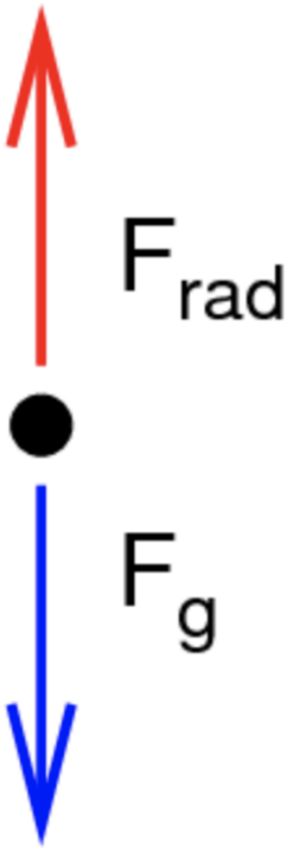
Eddington Limit



Consider force balance. Radiation force F_rad and gravitation F_g are written as below:

$$F_{\mathrm{rad}} = \frac{\sigma_{\mathrm{T}} S}{c}, \quad F_{\mathrm{g}} = \frac{GMm_{\mathrm{p}}}{r^2}$$

where σ_T is effective area of an electron when illuminated with radiation, S is energy flux L/4πr^2.

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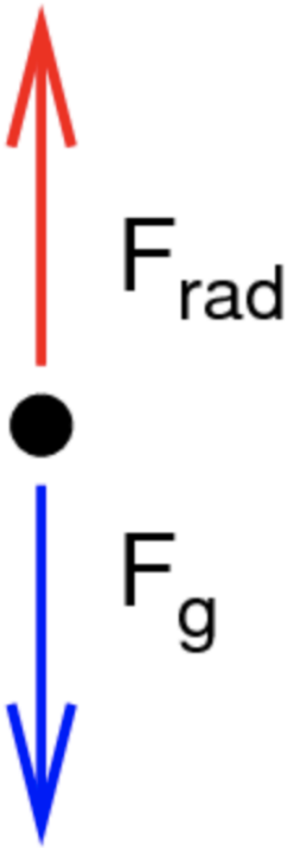
Eddington Limit



Accretion is possible when gravitation dominates:

$$F_{\rm rad} < F_{\rm g}$$

$$\therefore\ L < \underbrace{\frac{4\pi G M m_{\rm p} c}{\sigma_{\rm T}}}_{\text{Eddington luminosity}}$$

$$= 1.3 \times 10^{38}\,{\rm erg\,s^{-1}}\,\frac{M}{M_{\rm sun}}$$

$$\therefore\ \log m > -3.1 \quad (4)$$

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Mass-Radius Diagram

So far, 4 inequalities are gained:

$$\log r < -2.6 \quad (1)$$

$$\log r < \frac{1}{3}\log m - 3.7 \quad (2)$$

$$\log r > -\frac{1}{2}\log m - 6.6 \quad (3)$$

$$\log m > -3.1 \quad (4)$$

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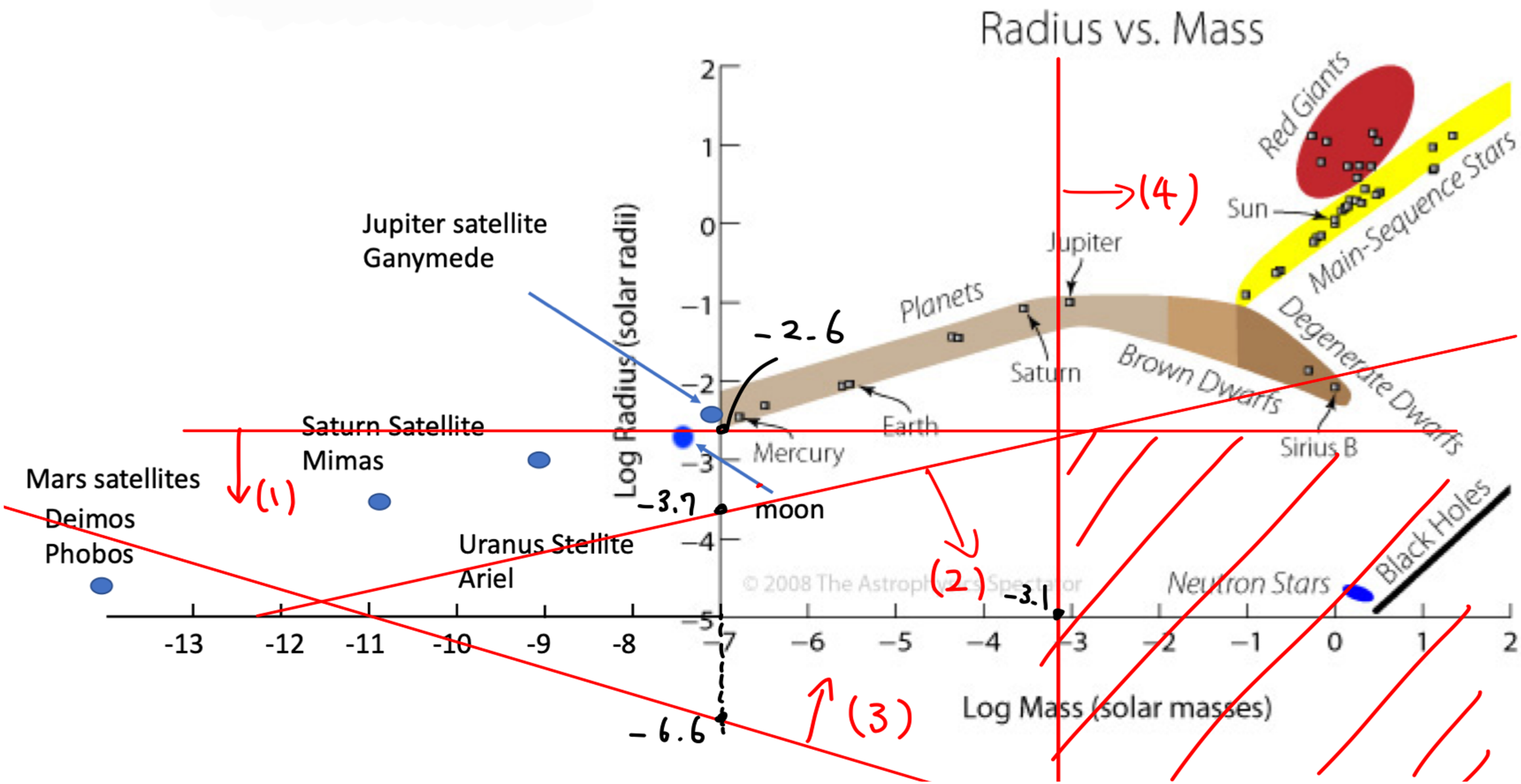
Mass Radius Diagram (4)



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Conclusion

On the diagram, core celestial body of Crab Nebula is restricted in the region of Neutron Stars and Black Holes.

A. Core celestial body of Crab Nebula is very likely a Neutron Star or Black Hole!!!

Back up

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Find rotational frequency

- Poisson distribution : $P(k;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$,

"fla $\lambda = \langle x_i \rangle$ (x_i : the counts in each light curve phase bin)

  - so the likelihood in the "flat line" (no pulse) model becomes simply

$$L = \prod_i P(x_i; \langle x_i \rangle)$$

- We calculate "flat line" model.
  - find the "worst" model - i.e. the one with <u>the strongest pulsations.</u>